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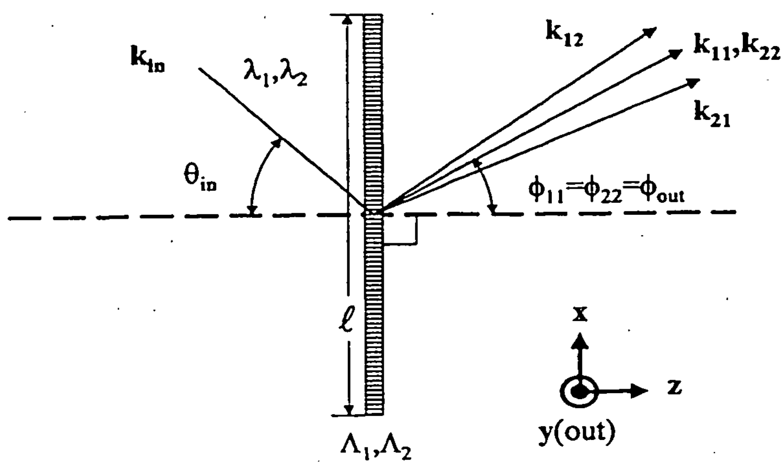

(57) Abstract

The present invention provides a composite grating structure that performs a programmed complex-valued, spectral filtering function on an input optical signal. The grating consists of a plurality of subgratings. Each subgrating controls the diffraction of a specific optical subbandwidth of light from an operative input direction to an operative output direction imparting a controllable amplitude and phase change onto the specific subbandwidth of light whose diffraction it controls within the overall operative bandwidth. The set of subgratings comprising the composite grating collectively controls the diffraction of an operative bandwidth of light from an operative input direction to an operative output direction. Each composite grating is programmed through their construction or through their dynamic modification to provide desired spectral filtering functions. While the composite gratings can be employed for general spectral filtering applications, they hold especially attractive potential in the area of optical waveform processing, generation, and detection.

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COMPOSITE DIFFRACTION GRATINGS FOR SIGNAL PROCESSING AND OPTICAL CONTROL APPLICATIONS

Field of the Invention:

The present invention relates to spectral filtering, optical communications, optical multiplexing, optical code-division multiple access, and optical code generation and detection.

Summary of the Present Invention:

The present invention provides a structure (i.e. a diffractive grating of unique design) which performs a programmed complex-valued, spectral filtering function on an input optical signal. The gratings fabricated in accordance with the present invention are composite gratings in the sense that they consist of a plurality of subgratings. Subgratings may be either physically distinct or exist only in the sense of a Fourier decomposition of a complex spatial profile. Each subgrating controls the diffraction of a specific optical subbandwidth of light from an operative input direction to an operative output direction. The set of subgratings comprising the composite grating collectively control the diffraction of an operative bandwidth of light from an operative input direction to an operative output direction. Each subgrating imparts a controllable amplitude and phase change onto the specific subbandwidth of light whose diffraction it controls within the overall operative bandwidth. Composite gratings according to the present invention are programmed through their construction or through their dynamic modification to provide desired spectral filtering functions. In the programming process, the physical parameters of the subgratings, such as spatial phase, amplitude, spatial period, and so on are configured and set so that each subgrating provides the desired amplitude and phase change to the subbandwidth whose diffraction it controls. While the composite gratings according to the present invention can be employed for general

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spectral filtering applications, they hold especially attractive potential in the area of optical waveform processing, generation, and detection. It is understood that optical waveforms can be coded so as to represent information and therefore the present invention applies to optical data processing, generation, and detection.

Composite gratings according to the present invention have numerous specific embodiments and settings. Composite gratings according to the present invention can be implemented as volume, surface, or waveguide gratings and constructed using frequency-selective active materials such as europium-doped yttrium oxide. They can be implemented in the same forms using active materials having no intrinsic frequency selectivity such as glass or lithium niobate. The key design element of the present composite grating invention is the use of subgratings, having either Fourier or physical definition, to control the diffraction of subbandwidths of light from an operative input to an operative output direction. Control here means that the structural properties of a subgrating determine the phase and amplitude factors that relate the output and input optical fields within the subbandwidth assigned to the subgrating. Typically the subgratings comprising a composite grating control subbandwidths that are substantially non-overlapping although absence of subbandwidth overlap is not necessary. It is necessary that the subbandwidths collectively controlled by the subgratings must span the full operative bandwidth of the composite grating.

Composite gratings according to the present invention are fundamentally different from grating devices known in the art. Known gratings accept multicolored light incident along a certain input direction and disperse it so that each color emerges along a path that is angularly separated from the paths of other incident colors. Composite gratings according to the present invention accept multicolored light incident along a certain input direction and diffract a portion of each color into the operative output direction while simultaneously modifying the relative amplitudes and phases of the various constituent colors.

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Composite grating devices after the present invention can be used, for example, in Optical Code-Division Multiple Access (OCDMA) data links. In this application, the composite grating devices are used to code optical signals within multiple communications channels with channel-specific time codes and then differentially detect channels based on their impressed time code. The ability to impress channel specific time-codes and then differentially detect on the basis of time-code allows for the multiplexing of multiple time-code differentiated optical communication channels on a single transport means. The composite surface gratings of the present invention can be utilized in any application area wherein the ability to effect spectral filtering is utilized, such as temporal pattern recognition, spectral equalization, optical encryption and decryption, and dispersion compensation.

Brief Description of the Figures:

Figure 1 is a diagram of the interaction of a bichromatic incident radiation field with a composite surface grating composed of two subgratings, causing the generation of output diffracted beams.

Figures 2A and 2B are depictions of the functioning of a composite diffraction grating in accordance with the present invention applied to temporal waveform recognition. The composite grating depicted is programmed through construction or dynamically to generate optical signals propagating along an operative output direction and having a recognition temporal waveform in response to optical signals incident on the grating along the operative input direction and possessing an specific address temporal waveform. The address and recognition waveforms are different and the recognition waveform is only generated in response to those input optical signals bearing the address temporal waveform. In Figure 2A, an optical signal whose temporal waveform is substantially similar to the address temporal waveform of the composite grating impinges on the grating along the operative input direction causing the generation of an optical signal propagating along the

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operative output direction and carrying the recognition temporal waveform. In Figure 2B, an optical signal whose temporal waveform is substantially different from the address temporal waveform programmed into the composite grating impinges on the grating causing the generation of an output signal whose temporal waveform differs substantially from the recognition waveform.

Description of Preferred Embodiments

By way of introduction, consider the transmission grating of width ℓ shown schematically in Figure 1. The grating is assumed to be translationally invariant along y, aligned with its surface normal coincident with z, and illuminated along a direction $k_i \perp y$ by a plane wave optical beam comprised of two wavelength components, $\lambda_i = c/\nu_i$ (i=1,2). We assume further that the grating has a surface profile, which characterizes its absorptive or phase response, comprised of a linear sum of two sinusoidal subgratings of wavelength Λ_j (j=1,2). The interaction of the bichromatic input beam with the two subgratings will in general create four output beams for each primary order of the grating. For specificity only, we assume that first order diffraction is depicted. The output directions are labeled k_{ij} corresponding to the interaction between the ith optical component with the jth subgrating. If $\lambda_1/\Lambda_1 = \lambda_2/\Lambda_2$, then, as shown in Figure 1, two of the output beams will be superimposed and comprise the operative output beam. The direction followed by the superimposed output beams is referred to as the operative output direction. Light propagating along the operative output direction can be isolated from light diffracted in other directions by suitable spatial filtering. The light beams and grating described here have been given a variety of attributes for purposes of exposition. The assignment of those attributes is not meant to be limiting in any fashion to the present invention. The attributes assigned for exposition purposes include: plane wave optical beam character, transmissive grating geometry, translational invariance

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along y, planar grating geometry, surface-plane grating location, sinusoidal subgrating character, and operation in the first diffractive order.

Generalizing the scenario of Figure 1 to N input frequencies and N subgratings, one may obtain an operative output beam having contributions from all input wavelengths wherein the contribution from each input wavelength is controlled by a specific subgrating. According to the present invention, by controlling the amplitudes and relative phases of the subgratings, one controls the amplitudes and phases of the optical spectral components in the operative output beam. In other words, the composite grating device constitutes a complex spectral filter with specific transfer function for a chosen operative input direction and a specific operative output direction.

Expressing these ideas more quantitatively, we assume that a general input beam may be expressed as a sum over N_ν discrete spectral components as

$$E_{in}(\mathbf{r},t)=\sum_{i=1}^{N_\nu} E_i(\mathbf{r},t)=\sum_{i=1}^{N_\nu} E_{i0}\exp\{2\pi i\nu_i[t-\mathbf{k}_{in}\bullet(\mathbf{r}-\mathbf{r}_0)/c]\}+c.c. \qquad [1]$$

where E_{i0} is complex and gives the phase and amplitude of the field component at frequency ν_i, $\boldsymbol{r_o}$ is a fixed reference position which we take to be the center of the grating, and $\boldsymbol{k_{in}}$ denotes the input beam's propagation direction. Optical signals carrying arbitrary temporal waveforms can be expanded as in Equation 1. In general, the spacing between frequency components must be comparable to or less than the inverse waveform duration and the expansion must encompass enough spectral components to cover the spectral range occupied by the optical signal. We assume that the grating is ruled with N_g multiple sinusoidal transmission subgratings whose summed amplitude transmission function is given by

$$T(\mathbf{r})=\sum_{j=1}^{N_g} a_j\left[1+\sin\left(2\pi\mathbf{K}_j\bullet(\mathbf{r}-\mathbf{r}_0)+\xi_j\right)\right] \qquad [2]$$

where a_j is real, $\boldsymbol{K_j}$ ($= x/\Lambda_j$) is the wavevector of the jth subgrating, $\mathbf{x}$ is a unit directional vector along the x-coordinate direction, Λ_j is the spatial period of the jth subgrating, and ξ_j is

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the spatial phase of the jth subgrating at r_0. The spatial phases of the subgratings, ξ_j, are of critical importance in the present invention for they provide control over the optical phases of the diffracted spectral components. The assumption that a_j is real, i.e. that the subgratings are amplitude only subgratings has been made for simplicity of illustration and is not meant to be limiting of the current invention. Amplitude or phase subgratings of quite general character, including a spatial dependence of a_j ($a_j = a_j(r)$), can be substituted without departing from the spirit of the present invention.

Invoking the Fraunhofer and thin grating limits, the diffracted output field resulting from the interaction of the ith input spectral component with the jth subgrating can be written as

$$E^{ij}_{out}(\mathrm{r},t) = H_{ij}E_{i0}\exp\left\{2\pi i\left[\nu_i\left(t-\mathrm{k}_{ij}\bullet\mathrm{r}/c\right)+\eta\left(\mathrm{r}_0\right)\right]\right\} \quad [3]$$

where

$$H_{ij} = \left(\frac{ma_j}{2i}\right)\exp\left(im\xi_j\right) \quad [4]$$

and $m = \pm 1$ depending on whether the subgrating is operated in the positive or negative first diffraction order. Note that in Figure 1, only the positive first diffraction order is depicted. k_{ij} is the output direction and $\eta(r_0) \equiv (\nu_i k_{in}/c - mK_j)\bullet r_0$ is an origin-dependent phase factor conveniently eliminated by choosing $r_0 = 0$. The diffraction integral leading to Equation 3 provides the usual constraint on input and output directions, k_{in} and k_{ij}, respectively, i.e.

$$\sin\theta_{in} - \sin\phi_{ij} = \frac{m\lambda_i}{\Lambda_j} \quad [5]$$

where θ_{in} is the chosen operative input angle and ϕ_{ij} is the output angle the ith wavelength component is diffracted by the jth subgrating, as shown in Figure 1. The assumptions of thin gratings and first order Fraunhofer diffraction are made herein for simplified illustration are not meant to be limiting in any fashion to the present invention.

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We now consider the special case in which $N_g = N_\nu = N$ and λ_i/Λ_j has the same constant value for all $i = j$. This second assumption guarantees that all diffracted beams having $i=j$ emerge along a common output direction, i. e. $\phi_{ii} = \phi_{out}$ ($i = j = 1,\ldots,N$). The angle ϕ_{out} is the operative output angle. The propagation vector corresponding to the operative output direction is designated k_{out}. The signal propagating in the operative output direction can be written as

$$E_{out}^{\phi_{out}}(\mathbf{r},t)=\sum_{i=1}^{N} H_{ii}E_{i0}\exp\{2\pi i[\nu_i(t-\mathbf{k}_{out}\bullet\mathbf{r}/c)]\} \qquad [6]$$

It will be noticed that $E_{out}^{\phi_{out}}(\mathbf{r},t)$ will encompass the full spectrum of the input beam when none of the subgratings have vanishing amplitude. By assumption each spectral component has been provided a subgrating configured to diffract a portion of the spectral component into the operative output direction. Each spectral component in the operative output beam is multiplied by a factor H_{ii} whose phase and amplitude is determined by the spatial phase and amplitude of the ith subgrating. $E_{out}^{\phi_{out}}(\mathbf{r},t)$ thus represents a spectrally filtered version of the input beam. The filtering function is determined through programming of the composite grating during its production or dynamically during its operation. An arbitrary filtering function $H(\nu)$ may be applied in discretized form provided the discretization is sufficiently fine. Eq. 6 indicates that a discretized form of the transfer function is applied if H_{ii} is set equal to $H(\nu_i)$. Eq. 4 then specifies the necessary amplitude and spatial phase for the subgrating that maps the subbandwidth of light in the vicinity of ν_i from the operative input to operative output direction.

In a first preferred embodiment, a set of subgratings is written upon the surface of a substrate to form a composite grating. The subgratings are operative to diffract incident radiation from a chosen operative input direction into a chosen operative output direction. In the process of mapping the optical signal impinging on the composite grating along the

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operative input direction into the operative output direction, the composite grating imparts a programmed spectral filtering function. In this embodiment, the programmed spectral filtering function acts to transform input pulses having a specific address temporal waveform into output pulses having a specific recognition temporal waveform. The composite grating in this instance effectively acts as a temporal waveform converter. This function can be employed so as to be equivalent to temporal waveform detection. The detection of output signals by electronic or other means preferentially sensitive to optical signals having waveforms substantially the same as the recognition waveform allows a user to conclude that input signals carried the address waveform. If the recognition temporal waveform is chosen to be a temporally brief and powerful pulse, its differential detection becomes especially convenient with devices known in the art.

Figures 2A and 2B show the operation of a composite surface grating used as a temporal waveform converter/detector in accordance with the present invention. In Figures 2A and 2B, an optical signal comprised of spectral components within the operative bandwidth of composite surface grating 102 and carrying optical waveform 100 impinges upon composite surface grating 102 along input path 101, triggering the generation of an optical signal carrying optical waveform 103 along output path 104. Input path 101 is substantially similar to the designed operative input path of composite surface grating 102 and output path 104 is substantially similar to the designed operative output path of composite grating 102. In Figure 2A, incident optical waveform 100A is substantially similar to the programmed address temporal waveform of composite grating 102, and output optical waveform 103A along operative output path 104 is substantially similar to the programmed recognition temporal waveform of composite grating 102. In Figure 2B, incident optical waveform 100B is substantially dissimilar to the programmed address temporal waveform of complex grating 102, and the output optical waveform 103B along operative output direction 104 is substantially dissimilar to the programmed recognition

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temporal waveform of complex grating 102. It is to be noted that any input signal propagating along 101 and containing spectral components within the operative bandwidth of the composite grating will produce an output signal along the operative output direction. However, the output signal will have the specific programmed recognition waveform only if the input signal has the programmed address waveform.

The design of a composite surface grating in accordance with this embodiment of the present invention is now considered. First specified are the address and recognition temporal waveforms and their central frequencies. The entire bandwidth of the latter must fall within the bandwidth of the former. A quantity of importance derivable from the waveforms specified is the minimal spectral structure width of optical signals carrying the address or recognition temporal waveforms. The Minimum Spectral Structure Width is the minimum frequency distance over which the Fourier spectra of optical signals laden with either the address or recognition waveform exhibit structure. Generally, the minimum spectral structure width can be set equal to the inverse of the larger of the address or recognition temporal waveform duration. The minimum spectral structure width is important because it sets the maximal frequency bandwidth that can be controlled by individual subgratings comprising the composite grating. This in turn means that subgratings must have a spectral resolution as fine as or finer than the minimum spectral structure width. The bandwidth of optical signals carrying the recognition waveform, $\delta\nu_{out}$, or address waveform, $\delta\nu_{in}$, are derivable from the respective waveforms specified. The minimum spectral structure width also represents the minimum spectral resolution needed to encode or program a spectral transfer function of interest into a composite grating.

In regards to the composite grating, its operative input and output directions must be specified. The operative input and output angles, and therefore subgrating periodicities, are chosen according to convenience according to equation 5 subject to substrate and production constraints that limit the range of subgrating periods that can be conveniently implemented.

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Choice of operative angles is also influenced by the need to make the spectral resolution of the subgratings finer than the minimal spectral structure width. The grating spectral resolution is given by

$$\delta\nu_g \equiv \left| \frac{c}{\ell(\sin\theta_{in} - \sin\phi_{out})} \right| , \qquad [7]$$

where c is the speed of light in the environment of the composite grating and ℓ is the subgrating width. For a fixed grating width, choice of operative angles providing the maximal angular change from input to output provides maximal spectral resolution. Providing for the operative output direction to be essentially anti-parallel to the operative input direction maximizes grating spectral resolution for fixed grating width.

The quantity $1/\delta\nu_g$, the grating processing time, is important as it provides an upper limit on the temporal length of the waveforms that can be distinguished with complete uniqueness. If a signal having duration longer than $1/\delta\nu_g$ is made incident on a composite grating, the instantaneous output signal will derive from a subduration of the input signal of approximate length $1/\delta\nu_g$.

The minimal number of required subgratings required, $N_{g,min}$, is equal to the bandwidth of the desired recognition temporal waveform divided by the minimal spectral structure width.

To construct the composite grating, it is necessary to determine its detailed surface structure. Decomposition of this structure into the sum of subgratings is the means used to determine the grating structure. Subgratings may exist as discrete physical entities as for example in a construction where the composite grating consists of multiple layers. Alternatively, subgratings may exist in the sense of elements of a Fourier decomposition of a single complex grating profile. In the latter case, the physical reality of subgratings may be highlighted by fabrication methods that build a complex grating structure through addition of

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multiple elements each of which imparts the functionality of a subgrating. For example, in holographic grating fabrication, a composite grating may be fabricated through multiple exposure wherein each exposure creates a subgrating with specific period, amplitude, and spatial phase. Through appropriate control of exposure parameters the subgrating parameters can be programmed so as to map a specific subbandwidth of light from the operative input direction to the operative output direction.

Now then, supposing that a composite grating is desired that detects an address temporal waveform $E_A(t)$ having Fourier spectrum $E_A(\nu)$. It is desired that the composite grating be operative to generate a short, powerful, output waveform (the recognition waveform) in the event that input optical signals carry the address temporal waveform. One spectral filtering function that will provide this operation is $H(\nu)=\alpha E^*_A(\nu)$, where α is a constant and $E^*_A(\nu)$ is the complex conjugate of $E_A(\nu)$. The spectral filtering function $H(\nu)$ is defined through $E_{out}(\nu)=H(\nu)E_{in}(\nu)$, where $E_{in}(\nu)$ and $E_{out}(\nu)$ are the spectra of optical signals incident along the operative input direction and emergent along the operative output direction, respectively.

To determine the subgrating parameters that provide a composite grating transfer function equal to $\alpha E^*_A(\nu)$, we spectrally decompose the input and address temporal waveforms in a discrete Fourier sum as in Eq. 1. The expansion coefficients for the input and address waveforms E_{i0} and E^A_{i0} respectively. Each complex expansion coefficient E^A_{i0} can be written as the product of a real amplitude and a complex phase factor, $E^A_{i0} = a^A_i \exp(i\xi_i)$. A field propagating in direction $\mathbf{k}_{out}$ that has been subjected to a filtering function $H(\nu)=\alpha E^*_A(\nu)$ should have the form

$$E_{corr}(\mathbf{r},t) \propto \sum_{i=1}^{N_\nu} E_{i0} E^{A*}_{i0} \exp\{2\pi i \nu_i (t - \mathbf{k}_{out} \bullet \mathbf{r}/c)\}. \qquad [8]$$

This expression is identical to the expression for $E^{\phi_{out}}_{out}(\mathbf{r},t)$ in Equation 6 if

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$$a_j = a_i^A \text{ and } \xi_j = -\xi_i \text{ (for all } i = j = 1,\ldots,N_n\text{)}. \qquad [9]$$

Note that Eq. 9 is a special case of the subgrating definition given above which has the form

$$H_{ii} = H(\nu_i), \qquad [10]$$

where in the present case $H(\nu)=\alpha E^*_A(\nu)$, H_{ii} refers to a specific subgrating as noted in relation to Eq. 4, and i denotes the i[th] frequency subbandwidth. If the subgratings are constructed to satisfy the conditions of Equation 9 or 10, the signals emerging from the composite grating along the operative output direction, k_{out}, will experience the filtering function $H(\nu)=\alpha E^*_A(\nu)$. In the time domain, the output signal will have a temporal waveform representing the cross correlation of the input waveform with the address waveform. As is known in the art, cross-correlation is an effective means of recognizing the similarity between waveforms. The cross-correlation consists primarily of a powerful, short pulse when the input and address waveforms ride on the same carrier frequency and are essentially identical.

The direct relationship between the amplitudes and phases of the subgratings comprising a composite grating and those of the Fourier components of the address waveform shown in Equation 9 demonstrates that the spatial profile of a composite grating programmed to recognize an address waveform is very simply related to the address waveform itself. The composite grating can be viewed as a spatial carrier wave having an envelope function. Examination of the equations above reveals that the spatial waveform of the composite grating is given by an appropriately scaled Fourier transform of the desired spectral filtering function.

Consider a composite grating designed as described above to create a short recognition waveform propagating along the operative output direction in response to a specific address temporal waveform incident along the operative input direction. If a short pulse is directed onto the composite grating anti-parallel to the operative output direction, an optical signal carrying the time-reversed address temporal waveform will emerge anti-

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parallel to the operative input direction. It is assumed in this paragraph that the bandwidth of the cited short pulse spans the bandwidth of the optical signals carrying the address waveform that the composite grating is designed to detect.

Multiple composite gratings can be superposed upon the same substrate to create a device capable of operating upon multiple input waveforms. The various composite gratings may have a common operative input direction and differing operative output directions wherein each composite grating and hence each operative output direction provides a different spectral filtering function. Conversely, the composite gratings may have a common, operative, output direction and differing, operative, input directions wherein each input direction produces output signals having experienced a different spectral filtering function. It is also possible that superimposed composite gratings each have unique operative input and output directions.

In a second preferred embodiment, a composite grating is configured so that its operative input and output directions lie anti-parallel along the line containing the subgrating spatial wavevector. In a further development of said second preferred embodiment, the composite grating is constructed to specifically accept and process input optical signals carrying a brief temporal waveform. In a separate further development of said second preferred embodiment, the composite grating is specifically programmed so as to produce output optical signals carrying a temporally brief recognition temporal waveform in response to input pulses carrying a specific address temporal waveform. In a fourth further development of said second preferred embodiment, said composite grating is embedded within the volume of a substrate of active material. In a fifth further development of said second preferred embodiment, said substrate consists of an optical waveguide which might be an optical fiber. In a sixth further development of said second preferred embodiment, said subgratings possess a position dependent amplitude and phase, leading to a position dependent reflectivity.

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According to Equation 7, the maximal processing time of a composite grating will be achieved for $\theta_{in} = \pi/2$ and $\phi_{out} = -\pi/2$, i.e., the input direction is parallel to the subgrating wavevectors and the output direction is counter-propagating to the input direction. In this limit, the grating bandwidth becomes $\delta\nu_g = c/2\ell$. Maximization of the grating processing time or equivalently maximization of the grating spectral resolution is important as it enables minimization of the grating physical length needed for spectral transfer functions having a given minimum spectral structure width. The processing time of a composite grating having anti-parallel operative input and output directions (or any other geometry) can be increased if the grating is embedded within a substrate of refractive index n. In this case, the grating resolution bandwidth becomes $\delta\nu_g = c/2n\ell$, where here c is the speed of light in vacuum. For example, using a glass substrate with a refractive index of 1.5 leads to a fifty percent increase in the grating processing time for a fixed size or a concommitent reduction in grating size for a fixed processing time. Note that in this geometry ($\theta_{in}=\pi/2$), a given subgrating will only diffract light whose wavelength is less than or equal to the design wavelength for that subgrating.

Consider now the design of a composite grating wherein the operative input and output directions are anti-parallel and lie along the line defined by the subgrating wavevectors. We begin by specifying the spectral filtering function to be performed. As the input and output angles are chosen to be $\pi/2$ and $-\pi/2$ respectively, the spatial wavelength of each subgrating is equal, according to the diffraction condition, to ½ the wavelength of the subbandwidth that the particular subgrating is designed to diffract. If the light interacts with the grating while propagating within a material, it is the wavelength of light in the material that is referred to above. As the angles are fixed, the physical length, ℓ, of the grating must be chosen to ensure that the spectral resolution of the composite grating is sufficient to resolve the minimum spectral structure width characteristic of the desired spectral transfer

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function. Note that if the subgratings are embedded in a medium of index n, that it is the optical path length, $n\ell$, that determines the grating resolution rather than the physical length, ℓ.

Composite gratings wherein the operative input and output directions are anti-parallel and lie along the line containing the subgrating spatial wavevectors can be constructed within optical waveguides and optical fibers. In these cases, a subgrating typically comprises a periodic modulation of the index of refraction of the guided wave region, the cladding region, or both. The subgratings must be configured with spatial phases and amplitudes as needed to effect a desired spectral transfer function. In waveguide implementations of composite gratings that are designed to provide high efficiency diffraction, the amplitude of subgratings can be tapered to be relatively smaller at the input end of the composite grating and relatively larger at the opposite end. The taper serves to equalize the light backscattered as the input light is attenuated.

While we have repeatedly referred to the electromagnetic radiation incident on and diffracted from composite gratings as light, it is to be understood that composite gratings can be constructed operative to accept electromagnetic radiation from within any segment of the electromagnetic spectrum from radio, to microwave, to infrared, to visible, to ultraviolet, and beyond.

While the invention has been described with respect to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in format and detail may be made without departing from the spirit and scope of the invention.

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We claim:

1. A composite diffraction grating comprising an active material and an ordered assemblage of two or more periodic subgratings supported by said active material, wherein each subgrating controls the diffraction of a designed subbandwidth of radiation from a designed input direction to a designed output direction, said input directions and said output directions common to all subgratings, the ratio of the wavelength of a given subgrating to the wavelength of the subbandwidth of radiation controlled by said subgrating constant for all subgratings, and the amplitude and phase of the diffracted subbandwidth of radiation controlled by the amplitude and phase of the subgrating, such that the superposition of the outgoing waves results in the generation of an outgoing wave in the designed output direction with a designed output temporal waveform whenever the incident radiation is substantially similar to a designed input temporal waveform along the designed input direction.

2. A composite grating device comprising an active material and an ordered assemblage of two or more sets of two or more periodic subgratings per set supported by said active material, wherein each subgrating controls the diffraction of a subbandwidth of radiation from a designed input direction to a designed output direction, said input directions and said output directions common to all subgratings within a given set, the ratio of the wavelength of a given subgrating to the wavelength of the subbandwidth of radiation controlled by said subgrating constant for all subgratings within a given set, the ratio of the wavelength of a given subgrating to the wavelength of the subbandwidth of radiation controlled by said subgrating in a first set not equal to the ratio of the wavelength of a given subgrating to the wavelength of the subbandwidth of radiation controlled by said subgrating in a second set, and the amplitude and phase of the diffracted subbandwidth of radiation controlled by the amplitude and phase of the subgrating, such that the superposition of the outgoing waves results in the generation of an outgoing wave in the

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designed output direction for a given set with a designed output temporal waveform for said given set whenever the incident radiation is substantially similar to a designed input temporal waveform for said given set along the designed input direction for said given set.

3. An optical encoder, comprising the composite grating of claim 1, wherein the input temporal waveform comprises a substantially short pulse with a temporal duration on the order of the inverse bandwidth of said input temporal waveform and the output temporal waveform comprises a temporally structured waveform with a temporal duration substantially larger than the inverse bandwidth of said output temporal waveform.

4. An optical decoder comprising the composite grating of claim 1, wherein the input temporal waveform comprises a temporally structured waveform with a temporal duration substantially larger than the inverse bandwidth of said input temporal waveform and the output temporal waveform comprising a substantially brief pulse with a temporal duration on the order of the inverse bandwidth of said output temporal waveform.

5. The composite diffraction grating of claim 1, wherein the input direction is parallel to the wavevectors of the subgratings.

6. The composite diffraction grating of claim 5, wherein the output direction is counterpropagating to the input direction.

7. The composite diffraction grating of claim 5, wherein the active material comprises an optical waveguide.

8. The composite diffraction grating of claim 7, wherein the active material comprises an optical fiber.

9. The composite diffraction grating of claim 1, wherein the amplitude of a given subgrating depends upon the spatial position within the active material.

10. The composite diffraction grating of claim 9, wherein the active material comprises an optical waveguide.

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11. The composite diffraction grating of claim 10, wherein the optical waveguide comprises an optical fiber.

12. The composite diffraction grating of claim 1, wherein the operative subgratings reflect the subbandwidths of radiation controlled by said subgratings into the designed output direction.

13. The composite diffraction grating of claim 1, wherein the operative subgratings transmit the subbandwidths of radiation controlled by said subgratings into the designed output direction.

14. The composite diffraction grating of claim 1, wherein the operative subgratings have a sinusoidal spatial profile.

15. The composite diffraction grating of claim 1, wherein the operative subgratings have a nonsinusoidal spatial profile.

16. The composite diffraction grating of claim 1, wherein the operative subgratings are characterized by a spatial profile with periodic variations in the transmission or reflection amplitude, i.e. amplitude subgratings.

17. The composite diffraction grating of claim 1, wherein the operative subgratings are characterized by a spatial profile with periodic variations in the transmission or reflection phase, i.e. phase subgratings.

18. The composite diffraction grating of claim 1, wherein the operative subgratings are characterized by a spatial profile with periodic variations in the transmission or reflection amplitude and phase, i.e. complex subgratings.

19. The diffraction grating device of claim 2, wherein each set of subgratings is distinguished by the direction of the subgrating wave vectors.

20. The composite diffraction grating of claim 1, wherein the operative subgratings exist in the sense of elements of a Fourier decomposition of a single complex grating profile.

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21. The composite diffraction grating of claim 20, wherein the operative subgratings exist in the sense of elements of a Fourier decomposition of a single spatial carrier wave modified by a designed spatial modulation function.

22. An optical system for generating an output optical waveform from an input optical waveform having a carrier frequency, by directing said input optical waveform through a passive periodic structure, said passive periodic structure characterized by being a complex set of subgratings, each of which has a specific wavelength, direction, amplitude and phase.

23. A passive periodic structure which performs a spectral filtering function on an input optical field, said structure characterized by one or more sets of subgratings, each set of subgratings controlling the diffraction of incident radiation according to the input temporal waveform and the input direction of the incident radiation, whereby if the input temporal waveform and the input direction match the designed input temporal waveform and designated input direction of the set of subgratings, the set of subgratings will trigger the creation of a designated output temporal waveform along a designated output direction.

24. A passive periodic structure which performs a spectral filtering function on an input optical field to produce output radiation, said structure characterized by one or more sets of subgratings, the amplitude and phase of the outgoing radiation at the designated frequency being controlled by the amplitude and phase of the subgratings.

25. An optical system which has an input optical beam of N input wavelengths, characterized by a passive periodic structure comprising N sub-gratings which produce a common output beam having contributions from all input wavelengths wherein the contribution from each input wavelength is controlled by a specific subgrating.

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The present invention provides a composite grating structure that performs a programmed complex-valued, spectral filtering function on an input optical signal. The gratings fabricated in accordance with the present invention are composite gratings consisting of a plurality of subgratings. Each subgrating controls the diffraction of a specific optical subbandwidth of light from an operative input direction to an operative output direction imparting a controllable amplitude and phase change onto the specific subbandwidth of light whose diffraction it controls within the overall operative bandwidth. The set of subgratings comprising the composite grating collectively control the diffraction of an operative bandwidth of light from an operative input direction to an operative output direction. Each composite grating according to the present invention is programmed through their construction or through their dynamic modification to provide desired spectral filtering functions. While the composite gratings according to the present invention can be employed for general spectral filtering applications, they hold especially attractive potential in the area of optical waveform processing, generation, and detection.

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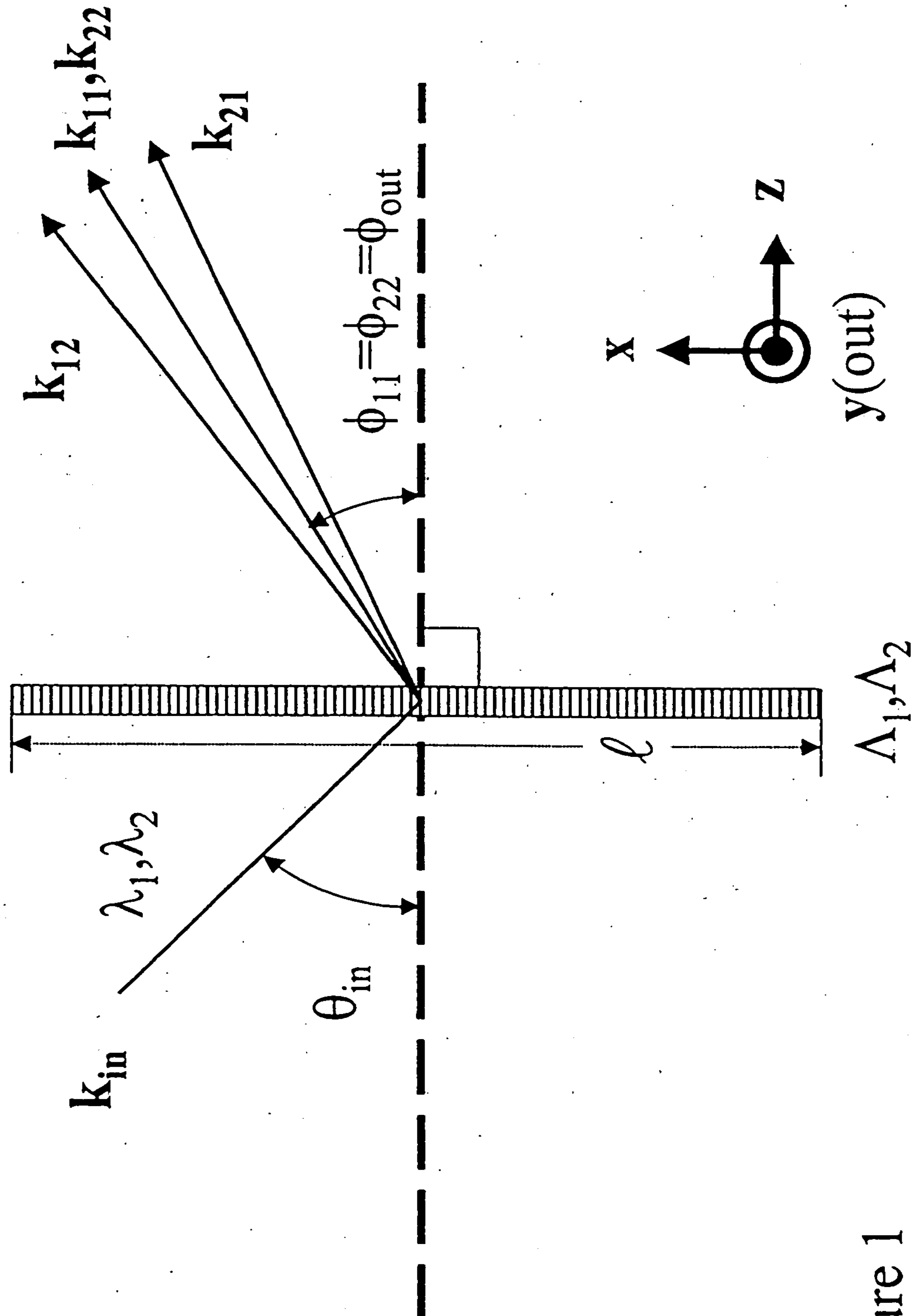

k_{12}
k_{11}, k_{22}
k_{21}
$\phi_{11}=\phi_{22}=\phi_{out}$
x
z
y(out)
k_{in}
θ_{in}
λ_1, λ_2
ℓ
Λ_1, Λ_2

Figure 1

Figure 2A

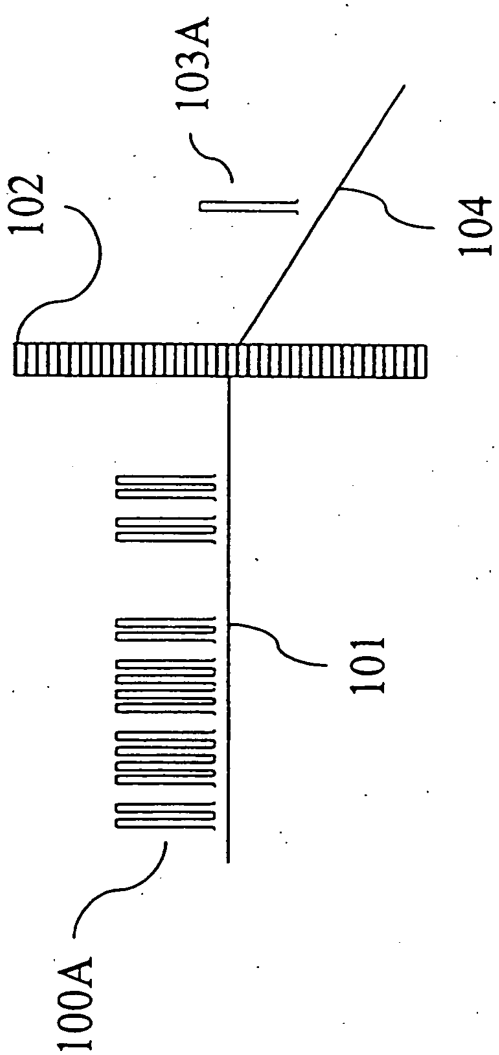
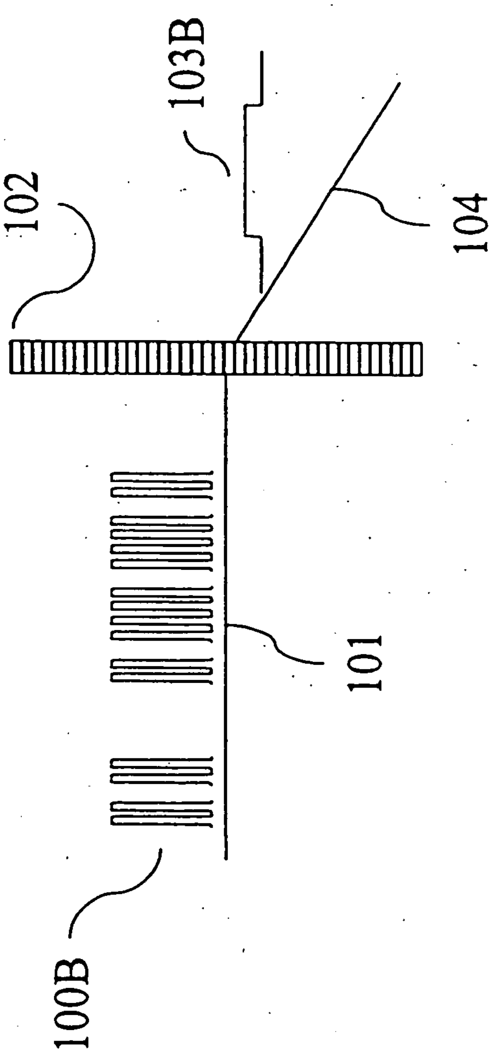


Figure 2B



INTERNATIONAL SEARCH REPORT

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A. CLASSIFICATION OF SUBJECT MATTER

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B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 385/37; 372/102; 250/237G, 231.13; 359/10, 11, 559, 566, 569

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

none

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

none

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X ---- A	US 5,040,188 A (LANG ET AL) 13 August 1991 (13/08/91), see entire document, especially column 1, lines 1-68.	1-2, 5-21 -------------- 3, 4
X	US 5,315,423 A (HONG) 24 May 1994 (24/05/94), see entire document.	22-23
X	US 5,204,524 A (ICHIKAWA ET AL) 20 April 1993 (20/04/93), see lines 3-54 of column 4.	24
X	US 4,387,955 A (LUDMAN ET AL) 14 June 1983 (14/06/83), see entire document, especially column 7, lines 4-35	25

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

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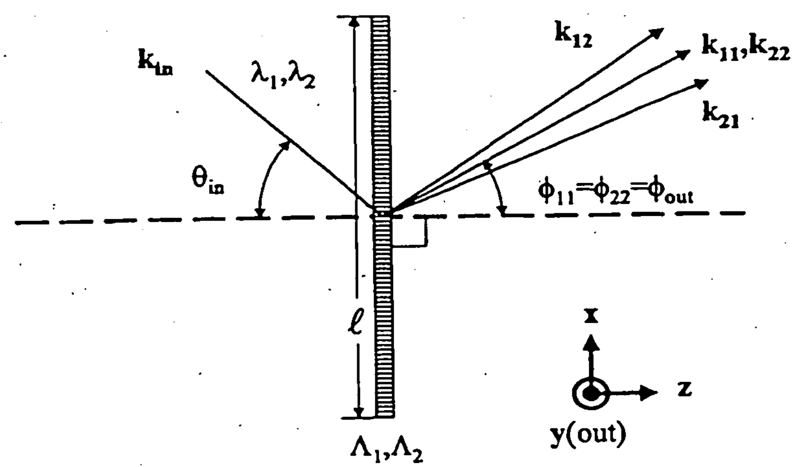

(57) Abstract

A composite grating structure is disclosed that performs a programmed complex-valued, spectral filtering function on an input optical signal. The grating consists of a plurality of subgratings, each controlling the diffraction of a specific optical subbandwidth of light from an operative input direction to an operative output direction imparting a controllable amplitude and phase change onto the corresponding subbandwidth of light. The set of subgratings comprising the composite grating collectively controls the diffraction of an operative output direction. Each composite grating is programmed through its construction or is dynamically modified to provide a desired spectral filtering function. The composite gratings can be employed for general spectral filtering application but are especially attractive for optical waveform processing, generation, and detection.

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